Measurement of W+W− production and search for the Higgs Boson in pp collisions at $\sqrt{s} = 7$ TeV

CMS Collaboration ; Amsler, C ; Chiochia, V ; Favaro, C ; Snoek, H ; Verzetti, M ; De Visscher, S ; Aguiló, E ; Schmitt, A ; Otyugova, P ; Storey, J ; Ivova, M ; Millan, B

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Measurement of W^+W^- Production and Search for the Higgs Boson in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

A measurement of W^+W^- production in pp collisions at $\sqrt{s} = 7$ TeV and a search for the Higgs boson are reported. The W^+W^- candidates are selected in events with two leptons, either electrons or muons. The measurement is performed using LHC data recorded with the CMS detector, corresponding to an integrated luminosity of 36 pb^{-1}. The $pp \to W^+W^-$ cross section is measured to be $41.1 \pm 15.3\,(\mathrm{stat}) \pm 5.8\,(\mathrm{syst}) \pm 4.5\,(\mathrm{lumi})$ pb, consistent with the standard model prediction. Limits on $WW\gamma$ and WWZ anomalous triple gauge couplings are set. The search for the standard model Higgs boson in the W^+W^- decay mode does not reveal any evidence of excess above backgrounds. Limits are set on the production of the Higgs boson in the context of the standard model and in the presence of a sequential fourth family of fermions with high masses. In the latter context, a Higgs boson with mass between 144 and 207 GeV/c^2 is ruled out at 95% confidence level.

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Dedicated to the memory of Ulrich Baur

*See Appendix A for the list of collaboration members

1 Introduction

The standard model (SM) of particle physics successfully describes the majority of high-energy experimental data [1]. One of the key remaining questions is the origin of the masses of W and Z bosons. In the SM, it is attributed to the spontaneous breaking of electroweak symmetry caused by a new scalar field [2–4]. The existence of the associated field quantum, the Higgs boson, has yet to be experimentally confirmed. The W^+W^- channel is particularly sensitive for the Higgs boson searches in the intermediate mass range ($120 - 200$ GeV/c^2).

Direct searches at the CERN LEP collider have set a limit on the SM Higgs boson mass of $m_H >$ 114.4 GeV/c^2 at 95% confidence level (C.L.) [5]. Precision electroweak measurements constrain the mass of the SM Higgs boson to be less than 185 GeV/c^2 at 95% C.L. [6]. Direct searches at the Tevatron exclude the SM Higgs boson in the mass range $158 - 175$ GeV/c^2 at 95% C.L. [7].

A possible extension to the SM is the addition of a fourth family of fermions [8, 9]. For sufficiently large lepton and quark masses, this extension has not been excluded by existing constraints. The presence of another fermion family produces an enhancement of the dominant gluon fusion cross section, together with some changes in the Higgs decay branching fractions. The choice of infinitely heavy quarks of the fourth family in the extended SM yields to the smallest enhancement factor for the Higgs boson cross section, hence to the most conservative scenario for the exclusion of such a model. This scenario is used to set limits in this paper.

The dominant irreducible background for $H \to W^+W^-$ production is the SM nonresonant production of W^+W^-. A good understanding of this process and its properties is thus needed for the Higgs boson search. The W^+W^- production has been extensively studied by the LEP and Tevatron experiments [10–15], where it has been found to be in agreement with the SM prediction. In pp collisions at the LHC, the SM next-to-leading order (NLO) QCD prediction of the W^+W^- production cross section at $\sqrt{s} = 7$ TeV is 43.0 ± 2.0 pb [16]. The W^+W^- production rates and differential cross sections are also sensitive to anomalous $WW\gamma$ and WWZ triple gauge boson couplings (TGC) [17, 18].

The first measurement of the W^+W^- cross section in pp collisions at $\sqrt{s} = 7$ TeV is reported here together with the results of the related search for the Higgs boson in the W^+W^- decay mode. The measurement is performed with data corresponding to an integrated luminosity of 35.5 ± 3.9 pb^{-1}, recorded with the Compact Muon Solenoid (CMS) detector, . The W^+W^- candidates, with both W bosons decaying leptonically, are selected in final states consisting of two isolated, high transverse momentum (p_T), oppositely-charged leptons (electrons or muons), and large missing transverse energy due to the undetected neutrinos. The search for the Higgs boson is performed in the 120 to 600 GeV/c^2 mass range, using both a cut-based event selection and a multivariate analysis. The search results are interpreted for both a SM Higgs boson and in the presence of a fourth family of fermions.

The paper is organized as follows. Section 2 briefly describes the main components of the CMS detector used in this analysis. Section 3 describes the W^+W^- production cross section measurement. The extraction of the limits on anomalous TGC is discussed in Section 4. The $H \to W^+W^-$ search procedure and results are presented in Section 5.

2 CMS Detector and Simulations

The CMS detector is described in detail elsewhere [19], while the key components for this analysis are summarized here. The central part of the CMS detector is a superconducting solenoid, which provides an axial magnetic field of 3.8 T parallel to the beam axis. Charged particle trajectories are measured by the silicon pixel and strip tracker, which covers the pseudorapidity region $|\eta| < 2.5$. Here, the pseudorapidity is defined as $\eta = -\ln\tan\theta/2$, where θ is the polar angle of the trajectory of the particle with respect to the direction of the counterclockwise beam. A crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL) surround the tracking volume and cover $|\eta| < 3.0$. A quartz-fiber Cherenkov calorimeter (HF) extends the coverage to $|\eta| = 5.0$. Muons are measured in gas detectors embedded in the iron return yoke outside the solenoid, in the pseudorapidity range $|\eta| < 2.4$. The detector is nearly hermetic, allowing for energy balance measurements in the plane transverse to the beam axis.

The first level of the trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than 1 ms, using information from the calorimeters and muon detectors. The High Level Trigger processor farm further decreases the event rate to a few hundred Hz, before data storage.

For this analysis, the $H \to W^+W^-$ and Drell–Yan processes are generated with the POWHEG program [20]. The $q\bar{q} \to W^+W^-$, $W+$jets, $t\bar{t}$ and the tW processes are generated with the MADGRAPH event generator [21], the $gg \to W^+W^-$ process is simulated with the GG2WW event generator [22], and the remaining processes are generated with PYTHIA [23]. A set of parton distribution functions (PDF) used for the simulated samples is CTEQ6L [24]. Calculations at next-to-next-to-leading order (NNLO) are used for the $H \to W^+W^-$ process, while NLO calculations are used for background cross sections. All processes are simulated using a detailed description of the CMS detector, based on the GEANT4 package [25].

3 Standard Model W^+W^- Cross Section Measurement

3.1 Event selection

Several SM processes can lead to a reconstructed final state similar to that of the W^+W^- signal. These backgrounds include instrumental contributions from $W+$jets and QCD multijet events where at least one of the jets is mis-identified as a lepton, top quark production ($t\bar{t}$ and tW), the Drell–Yan $Z/\gamma^* \to \ell^+\ell^-$ process, and diboson production ($W\gamma$, WZ and ZZ).

Events are selected with two high-p_T, oppositely-charged isolated leptons, in three final states: e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$. These final states thus include $W \to \tau\nu_\tau$ events with leptonic τ decays. The online event trigger requires the presence of a high-p_T electron or muon [26]. The trigger efficiency for signal events, which would be selected by the full offline event selection, is found to be above 98% in the $\mu^+\mu^-$ final state and above 99% in the e^+e^- and $e^\pm\mu^\mp$ final states.

Muon candidates are reconstructed combining two algorithms [27], one in which tracks in the silicon detector are matched to hits in the muon system, and another in which a global fit is performed on hits in both the silicon tracker and the muon system. All muon candidates are required to be successfully reconstructed by both algorithms and to have $p_T > 20$ GeV/c and $|\eta| < 2.4$. In addition, the track associated with the muon candidate is required to have at least 11 hits in the silicon tracker, to be consistent with a particle originating from the primary vertex in the event, and to have a high-quality global fit including a minimum number of hits in the muon detectors [26]. If more than one primary vertex is found for the same bunch crossing, only that with the highest summed p_T of the associated tracks is considered.

Electron candidates are reconstructed from clusters of energy deposits in the ECAL, which are then matched to hits in the silicon tracker. Seeded track trajectories are reconstructed with a "Combinatorial track finder" algorithm, and then fitted using a "Gaussian sum filter" algorithm, which takes into account bremsstrahlung emission as the electron traverses tracker material [28, 29]. Electron candidates are required to have $p_{\mathrm{T}} > 20$ GeV/c and $|\eta| < 2.5$. The electron candidate track is also required to be consistent with a particle originating from the primary vertex in the event. Electron identification criteria based on shower shape and track-cluster matching are applied to the reconstructed candidates. The criteria were optimized in the context of inclusive W and Z cross section measurements [26] and are designed to maximally reject misidentified electrons from QCD multijet production and nonisolated electrons from heavy-quark decays, while maintaining at least 80% efficiency for electrons from the decay of W or Z bosons. Electrons originating from photon conversions are suppressed by looking for a partner track and requiring no missing hits in the pixel detector for a track fit [29].

Charged leptons from W boson decays are expected to be isolated from any other activity in the event. For each lepton candidate, a cone of radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$ is constructed around the track direction at the event vertex. The activity around the lepton is determined from the scalar sum of the transverse energies of all tracks and all deposits in the ECAL and HCAL contained in the cone, with the exception of the lepton contributions. If this sum exceeds 15 (10)% of the muon p_{T} (electron E_{T}), the candidate is not selected.

Neutrinos from W boson decays escape detection, resulting in an imbalance of the energy in the projection perpendicular to the beam axis, called $E_{\mathrm{T}}^{\mathrm{miss}}$. The $E_{\mathrm{T}}^{\mathrm{miss}}$ measured from calorimeter energy deposits is corrected to take into account the contribution from muons and information from individual tracks reconstructed in the tracker to correct for the calorimeter response [30]. The event selection requires $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV to suppress the Drell–Yan background.

For the event selection also a derived quantity called *projected* $E_{\mathrm{T}}^{\mathrm{miss}}$ [14] is used. With $\Delta\phi$ the azimuthal angle between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest lepton, the projected $E_{\mathrm{T}}^{\mathrm{miss}}$ is defined as the component of $E_{\mathrm{T}}^{\mathrm{miss}}$ transverse to the lepton direction if $\Delta\phi$ is smaller than $\pi/2$, and the full magnitude of $E_{\mathrm{T}}^{\mathrm{miss}}$ otherwise. This variable helps to reject $Z/\gamma^* \to \tau^+\tau^-$ background events as well as $Z/\gamma^* \to \ell^+\ell^-$ events with misreconstructed $E_{\mathrm{T}}^{\mathrm{miss}}$ associated with lepton misreconstruction. Events are selected with projected $E_{\mathrm{T}}^{\mathrm{miss}}$ above 35 GeV in the e^+e^- and $\mu^+\mu^-$ final states, and above 20 GeV in the $e^\pm\mu^\mp$ final state that has lower contamination from $Z/\gamma^* \to \ell^+\ell^-$ decays. These requirements remove more than 99% of the Drell–Yan contribution.

To further reduce Drell–Yan background in the e^+e^- and $\mu^+\mu^-$ final states a Z veto is defined, by which events with a dilepton invariant mass within 15 GeV/c^2 of the Z mass are discarded. Events are also rejected with dilepton masses below 12 GeV/c^2 to suppress contributions from low mass resonances.

To reduce backgrounds containing top quarks, events containing jets with $|\eta| < 5.0$ and $p_{\mathrm{T}} > 25$ GeV/c are rejected. Jets are clustered from the particles reconstructed with the particle-flow event reconstruction [31–33], which combines the information from all CMS sub-detectors. The anti-k_{T} clustering algorithm [34] with distance parameter $R = 0.5$ is used. The jet veto is complemented by a *top veto* based on soft-muon and b-jet tagging [35, 36]. This veto allows further rejection of top quark background and also provides a way of estimating the remaining top quark background using the data.

To reduce the background from diboson processes, such as WZ and ZZ production, any event which has an additional third lepton passing the identification and isolation requirements is rejected.

Table 1 shows the W^+W^- efficiency, obtained from simulation of events, where both W bosons decay leptonically. As a cross-check, kinematic distributions are compared between data and simulation. Figure 1a shows the jet multiplicity distribution for events that pass all selections but the jet veto and top veto. Figure 1b shows the dilepton mass distribution for events passing the final W^+W^- event selections, except the Z mass veto.

Table 1: Selection efficiency for $WW \rightarrow \ell^+\ell^-$ events as obtained from simulation. The efficiency is normalized to the total number of events where both W bosons decay leptonically. Selections are applied sequentially. The efficiencies in parenthesis are defined relative to the previous cut.

Selection	e^+e^-	$e^+\mu^-/e^-\mu^+$	$\mu^+\mu^-$
lepton acceptance (η, p_T)	6.9%	13.4%	6.6%
primary vertex compatibility	6.2% (89.9%)	12.7% (94.9%)	6.5% (98.5%)
lepton isolation	5.2% (83.9%)	11.2% (88.2%)	6.1% (93.8%)
lepton identification	4.1% (78.8%)	9.6% (85.7%)	5.6% (91.8%)
γ conversion rejection	3.9% (95.1%)	9.4% (97.9%)	5.6% (100.0%)
$E_T^{miss} > 20$ GeV	3.2% (82.5%)	7.7% (82.5%)	4.6% (82.4%)
$m_{\ell\ell} > 12$ GeV/c^2	3.2% (100.0%)	7.7% (100.0%)	4.6% (100.0%)
Z mass veto	2.5% (77.1%)	7.7% (100.0%)	3.5% (77.2%)
projected E_T^{miss}	1.5% (61.3%)	6.7% (86.7%)	2.2% (63.1%)
jet veto	0.9% (60.8%)	4.2% (62.3%)	1.4% (61.4%)
extra lepton veto	0.9% (100.0%)	4.2% (100.0%)	1.4% (100.0%)
top veto	0.9% (100.0%)	4.1% (99.4%)	1.4% (100.0%)

After applying all selection requirements, 13 events are observed in data, with 2, 10, and 1 events coming from e^+e^-, $e^\pm\mu^\mp$, and $\mu^+\mu^-$ final states, respectively, in good agreement with simulation based expectations (13.5 ± 0.3, 2.7 ± 0.1, 2.3 ± 0.2 and 8.5 ± 0.3 respectively).

3.2 Background estimation

To evaluate the remaining background contributions in data, a combination of techniques based on data and on detailed simulation studies are used.

The accurate simulation of the W + jets and QCD multijet instrumental background suffers from large systematic uncertainties, which are hence estimated with a data-based approach. A set of loosely selected lepton-like objects is defined in a sample of events dominated by di-jet production. The probability is calculated for those objects that are misidentified as leptons passing all lepton selection criteria. This misidentification probability, parameterized as a function of p_T and η, is then applied to a sample of events selected using the final selection criteria, except for one of the leptons for which the selection has been relaxed to the looser criteria and that has failed the nominal selection. This procedure is validated in simulated events and applied on data. The systematic uncertainty on this estimation is obtained by applying the same method to another control sample with different selection criteria. A value of 50% is derived from a closure test, where a tight-to-loose rate derived from QCD simulated events is applied to a W + jets simulated sample to predict the rate of events with one real and one misidentified lepton. The total misidentified electron and muon background contributions are found to be 1.2 ± 0.3 (stat) ± 0.6 (syst) and 0.5 ± 0.3 (stat) ± 0.3 (syst) events, respectively.

The remaining top quark background after full event selection can be estimated from data by counting events with either an additional soft muon (well identified muons with $p_T > 3$ GeV/c are considered) or at least one b-tagged jet with p_T below the jet veto threshold. No events are rejected by the top-veto in data after applying the full selection, which is consistent with the predictions from simulation. Therefore, the top quark background contribution is taken directly from simulation, which predicts 0.77 ± 0.05 (stat) ± 0.77 (syst) events, where a 100%

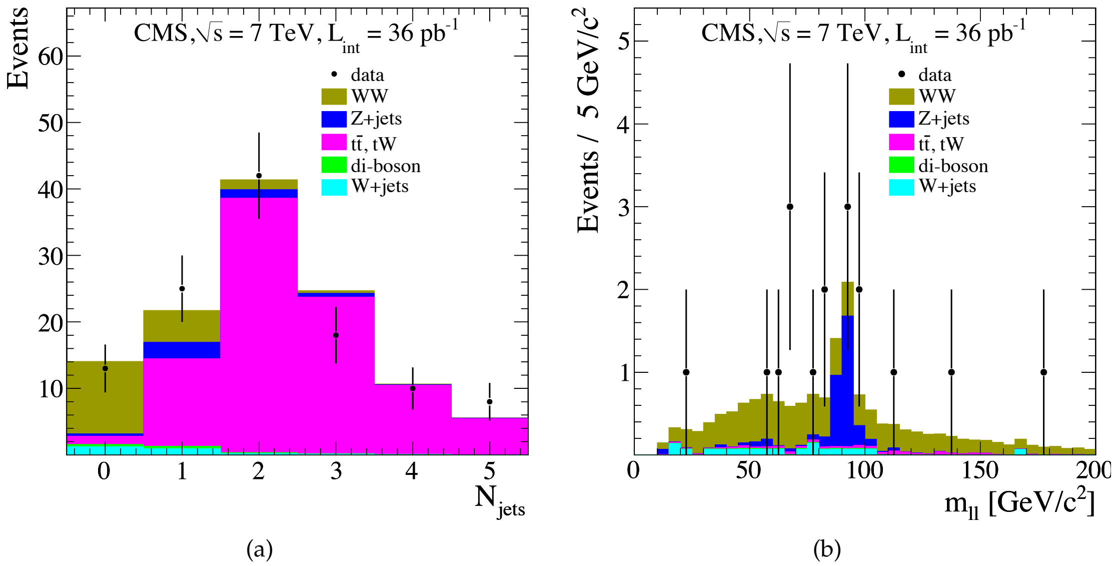


Figure 1: (a) Jet multiplicity distribution after all W^+W^- selection criteria, except the top veto and jet veto requirements. (b) Dilepton mass distribution for the events passing the final selections, except the Z mass veto.

systematic uncertainty is assigned as a conservative estimate of the difference between data and simulation.

An estimate of the residual Z boson contributions in the e^+e^- and $\mu^+\mu^-$ final states outside the Z mass window, $N_{\mathrm{out}}^{\ell\ell,\mathrm{exp}}$, is obtained from data in the following way. The ratio $R_{\mathrm{out/in}}^{\ell\ell}$ of the number of events outside the Z mass window to that inside is obtained from simulation. The observed number of events inside the Z mass window in data, $N_{\mathrm{in}}^{\ell\ell}$, from which the non-Z contributions ($N_{\mathrm{in}}^{\mathrm{non-Z}}$) is subtracted, is then scaled by $R_{\mathrm{out/in}}^{\ell\ell}$ to compute the residual Z background:

$$N_{\mathrm{out}}^{\ell\ell,\mathrm{exp}} = R_{\mathrm{out/in}}^{\ell\ell}(N_{\mathrm{in}}^{\ell\ell} - N_{\mathrm{in}}^{\mathrm{non-Z}}), \text{ with } R_{\mathrm{out/in}}^{\ell\ell} = N_{\mathrm{out}}^{\ell\ell,\mathrm{MC}} / N_{\mathrm{in}}^{\ell\ell,\mathrm{MC}}.$$

The number $N_{\mathrm{in}}^{\mathrm{non-Z}}$ is estimated as half of the number of $e^{\pm}\mu^{\mp}$ events, taking into account the relative detection efficiencies of electrons and muons. The result also includes WZ and ZZ contributions, in which both leptons come from the same Z boson. The total Z decay contribution is estimated as 0.2 ± 0.2 (stat) ± 0.3 (syst) events. The systematic uncertainty of this method arises primarily from the dependence of $R_{\mathrm{out/in}}^{\ell\ell}$ on the $E_{\mathrm{T}}^{\mathrm{miss}}$ cut.

Other backgrounds are estimated from simulation. The $W\gamma$ production, where the photon is misidentified as an electron, is suppressed by the γ conversion rejection requirements. As a cross-check, this background was studied using the events passing all selection requirements, except that the two leptons must have the same charge. This sample is dominated by W + jets and $W\gamma$ events. Other minor backgrounds are WZ and ZZ diboson production where the selected leptons come from different bosons, and $Z/\gamma^* \to \tau^+\tau^-$ production. All background predictions are summarized in Table 2. The estimated number of remaining background events is 3.29 ± 0.45 (stat) ± 1.09 (syst).

Table 2: Summary of background estimations for $W^+W^- \to 2\ell 2\nu$ at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 36 pb^{-1}. Statistical and systematic uncertainties are reported.

Process	Events
W+jets + QCD	$1.70 \pm 0.40 \pm 0.70$
$t\bar{t}$ + tW	$0.77 \pm 0.05 \pm 0.77$
$W\gamma$	$0.31 \pm 0.04 \pm 0.05$
$Z + WZ + ZZ \to e^+e^- / \mu^+\mu^-$	$0.20 \pm 0.20 \pm 0.30$
$WZ + ZZ$, leptons not from the same boson	$0.22 \pm 0.01 \pm 0.04$
$Z/\gamma^* \to \tau^+\tau^-$	$0.09 \pm 0.05 \pm 0.09$
Total	$3.29 \pm 0.45 \pm 1.09$

3.3 Efficiencies and systematic uncertainties

The W^+W^- signal efficiency is estimated using the simulation, corrected by data-to-simulation *scale factors*. For electron and muon reconstruction and identification, a tag-and-probe method [26] is applied to leptons from $Z/\gamma^* \to \ell^+\ell^-$ events in the Z resonance region, both in data and simulation. The scale factors are found to be consistent with unity for muons. For electrons, they are found to be $(96.9 \pm 1.9)\%$ and $(99.2 \pm 2.6)\%$ in the barrel ($|\eta| < 1.479$) and end-cap ($|\eta| \geq 1.479$) regions, respectively. For estimating the effect of the jet veto efficiency on the W^+W^- signal, events in the Z resonance region are used according to the following relation: $\epsilon^{data}_{W^+W^-} = \epsilon^{MC}_{W^+W^-} \times \epsilon^{data}_{Z} / \epsilon^{MC}_{Z}$. The scale factor is found to be consistent with unity. The uncertainty is factorized into the uncertainty on the Z efficiency in data (ϵ^{data}_{Z}) and the uncertainty on the ratio of the W^+W^- efficiency to the Z efficiency in simulation ($\epsilon^{MC}_{W^+W^-} / \epsilon^{MC}_{Z}$). The uncertainty on the former, which is statistically dominated, is 0.3%. Theoretical uncertainties due to higher-order corrections contribute most to the W^+W^-/Z efficiency ratio uncertainty, which is estimated to be 5.5% for W^+W^- production from the uncertainties on the jet kinematics for W^+W^- and Z events from different NLO Monte Carlo generators.

The acceptance uncertainties due to PDF choice range from 2% to 4% for the different processes [37, 38]. The uncertainties from lepton identification and trigger requirements range from 1% to 4%. The effect on the signal efficiency from multiple collisions within a bunch crossing is 0.5%, as evaluated by reweighting the number of reconstructed primary vertices in simulation to match the distribution found in data. The uncertainty from the luminosity measurement is 11% [39]. Overall the uncertainty is estimated to be 7% on the W^+W^- selection efficiency, coming mainly from the theoretical uncertainty in the jet veto efficiency determination. The uncertainty on the background estimations in the W^+W^- signal region, reported in Table 2, is about 37%, dominated by statistical uncertainties in the data control regions.

3.4 W^+W^- cross section measurement

The W^+W^- yield is calculated from the number of events in the signal region, after subtracting the expected contributions of the various SM background processes. From this yield and the $W \to \ell\nu$ branching fraction [1], the W^+W^- production cross section in pp collisions at $\sqrt{s} =$ 7 TeV is found to be

$$\sigma_{W^+W^-} = 41.1 \pm 15.3\,(\text{stat}) \pm 5.8\,(\text{syst}) \pm 4.5\,(\text{lumi})\,\text{pb}.$$

This measurement is consistent with the SM expectation of 43.0 ± 2.0 pb at NLO [16].

The WW to W cross section ratio is also computed. In this ratio, the luminosity uncertainty cancels out, and uncertainties for the signal efficiency and background contamination can be considered mostly uncorrelated, since the correlated factors form a very small fraction of the overall uncertainty. The W$\rightarrow \ell\nu$ cross section is taken from Ref. [26] to obtain the following cross section ratio:

$$\frac{\sigma_{WW}}{\sigma_W} = (4.46 \pm 1.66 \pm 0.64) \cdot 10^{-4},$$

in agreement with the expected theoretical ratio $(4.45 \pm 0.30) \cdot 10^{-4}$ [16, 40, 41].

4 Limits on WWγ and WWZ Anomalous Triple Gauge Couplings

A measurement of triple gauge couplings is performed and limits on anomalous couplings are set, using the effective Lagrangian approach with the HISZ parametrization [42] without form factors. Three parameters, λ_Z, κ_γ, and g_1^Z, are used to describe all operators which are Lorentz and $SU(2)_L \otimes U(1)_Y$ invariant and conserve C and P separately. In the SM, $\lambda_Z = 0$ and $\kappa_\gamma = g_1^Z = 1$. In this paper, $\Delta\kappa_\gamma$ and Δg_1^Z are used to denote the deviation of the κ_γ and g_1^Z parameters with respect from the SM values. Two different measurements of the anomalous couplings are performed. Both use the leading lepton p_T distribution. The first measurement uses a binned fit, while the second uses an unbinned fit to data. The uncertainties on the quoted luminosity, signal selection, and background fraction are assumed to be Gaussian, and are reflected in the likelihood function used to determine the limits in the form of nuisance parameters with Gaussian constraints.

Figure 2 shows the leading lepton p_T distributions in data and the predictions for the SM W^+W^- signal and background processes, and for a set of large anomalous couplings. Table 3 presents the 95% C.L. limits on one-dimensional fit results for anomalous TGC that correspond to the change in the log-likelihood of 1.92. Both methods give similar results, consistent with the SM. The limits are comparable to the current Tevatron results [14, 15]. In Fig. 3 the contour plots of the 68% and 95% C.L. for the $\Delta\kappa_\gamma = 0$ and $\Delta g_1^Z = 0$ scenarios are displayed. The contours correspond to the change in the log-likelihood of 1.15 and 2.99 respectively.

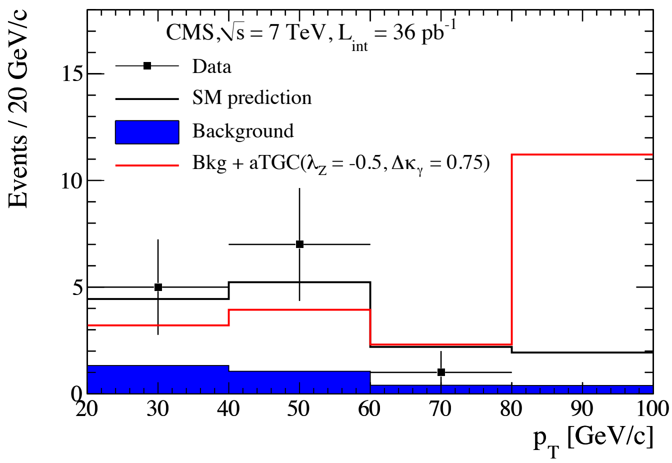


Figure 2: Leading lepton p_T distribution in data overlaid with predictions from the SM simulation, background only simulation (*Bkg* in the figure) and the simulation with large anomalous couplings (*aTGC* in the figure).

Table 3: 95% C.L. limits on one-dimensional fit results for anomalous TGC.

	λ_Z	Δg_1^Z	$\Delta\kappa_\gamma$
Unbinned fit	$[-0.19, 0.19]$	$[-0.29, 0.31]$	$[-0.61, 0.65]$
Binned fit	$[-0.23, 0.23]$	$[-0.33, 0.40]$	$[-0.75, 0.72]$

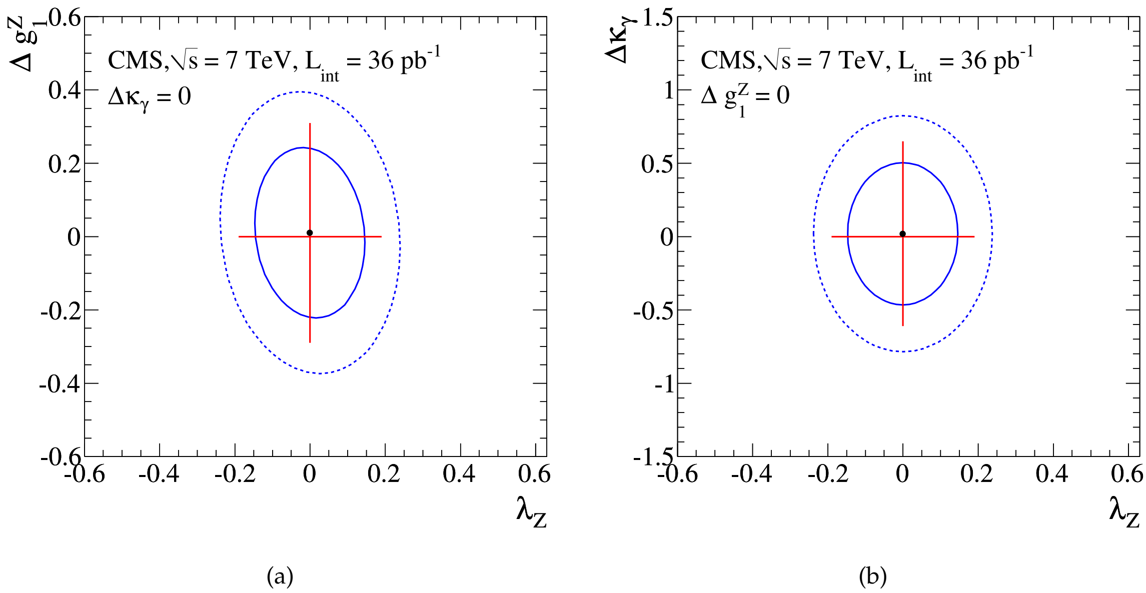


Figure 3: 68% (solid blue lines) and 95% C.L. (dotted blue lines) as well as the central value (point) and one-dimensional 95% C.L. limits (red lines) using unbinned fits, for (a) $\Delta\kappa_\gamma = 0$ and (b) $\Delta g_1^Z = 0$.

5 Search for Higgs Bosons in the W^+W^- Decay Mode

The preselection for the Higgs boson search in the W^+W^- decay mode is identical to the W^+W^- selection described in Section 3.1. To enhance the sensitivity to the Higgs boson signal, two different analyses are performed. The first analysis is a cut-based approach where further requirements on a few observables are applied, while the second analysis makes use of multivariate techniques. Both of them cover a large Higgs boson mass (m_H) range, and each is separately optimized for different m_H hypotheses. The first method is the simplest approach to be performed on the limited recorded data sample. The second one is more powerful, since it exploits the information present in the correlation among the variables.

5.1 Search strategy

In the cut-based approach, the extra selections are based on the transverse momenta of the harder ($p_T^{\ell,\max}$) and the softer ($p_T^{\ell,\min}$) leptons, the dilepton mass $m_{\ell\ell}$, and the azimuthal angle difference $\Delta\phi_{\ell\ell}$ between the two selected leptons. Among these variables, $\Delta\phi_{\ell\ell}$ provides the best discriminating power between the Higgs boson signal and the majority of the backgrounds in the low mass range [43]. Leptons originating from $H \to W^+W^-$ decays tend to have a relatively small opening angle, while those from backgrounds are preferentially emitted back-to-back. Figure 4 shows the $\Delta\phi_{\ell\ell}$ distribution, after applying the W^+W^- selections, for a SM Higgs boson signal with $m_H = 160\ \mathrm{GeV}/c^2$, and for backgrounds.

Because the kinematic properties of the Higgs boson decay depend on its mass, the selection criteria were optimized for each assumed mass value. The requirements are summarized in Table 4. The numbers of events observed in 36 pb^{-1} of data, with the signal and background predictions are listed in Table 5.

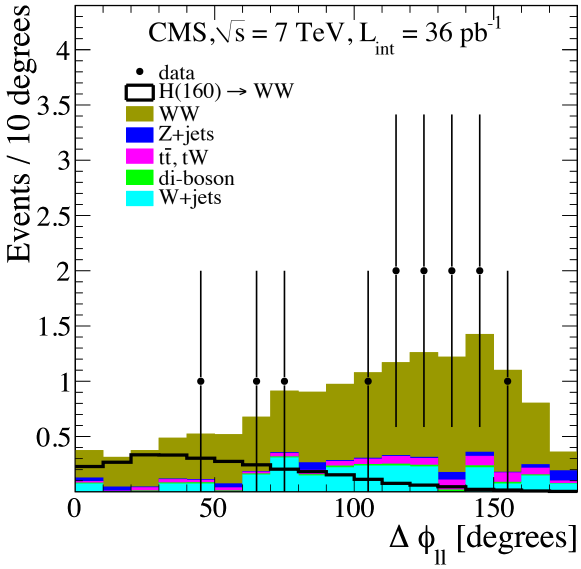


Figure 4: Azimuthal angular separation between the two selected leptons after W^+W^- selection, for $m_H = 160$ GeV/c^2 SM Higgs signal and for backgrounds. The area marked as W^+W^- corresponds to the nonresonant contribution.

Table 4: Values of the selection requirements for several m_H mass hypotheses.

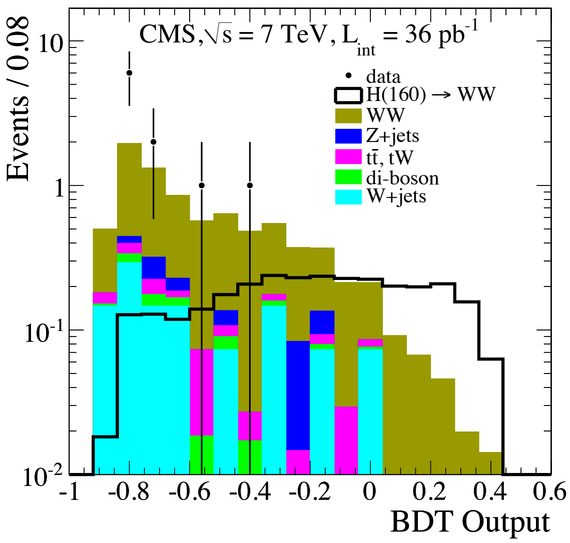
m_H (GeV/c^2)	$p_T^{\ell,\max}$ (GeV/c) $>$	$p_T^{\ell,\min}$ (GeV/c) $>$	$m_{\ell\ell}$ (GeV/c^2) $<$	$\Delta\phi_{\ell\ell}$ (degree) $<$
130	25	20	45	60
160	30	25	50	60
200	40	25	90	100
210	44	25	110	110
400	90	25	300	175

In the multivariate approach a boosted decision tree (BDT) technique [44] is used for each Higgs boson mass hypothesis. In addition to the W^+W^- selection requirements, a loose cut on the maximum value of $m_{\ell\ell}$ is applied to enhance the signal-to-background ratio. The multivariate technique uses the following additional variables compared to the cut-based analysis: $\Delta R_{\ell\ell} \equiv \sqrt{\Delta\eta_{\ell\ell}^2 + \Delta\phi_{\ell\ell}^2}$ between the leptons, $\Delta\eta_{\ell\ell}$ being the η difference between the leptons, which has similar properties as $\Delta\phi_{\ell\ell}$; the angles in the transverse plane between E_T^{miss} and each lepton, which discriminates against events with no real E_T^{miss}; the projected E_T^{miss}; the transverse mass of both lepton-E_T^{miss} pairs; and finally lepton flavours.

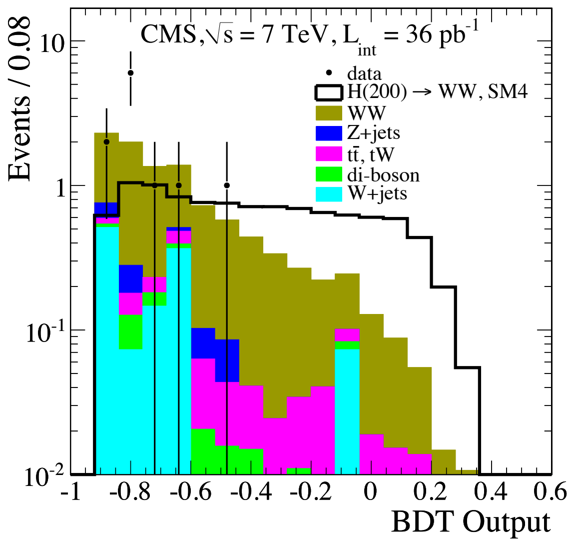
The BDT outputs for $m_H = 160$ GeV/c^2 and $m_H = 200$ GeV/c^2 are shown in Fig. 5. The Higgs boson event yield is normalized to the SM expectation in Fig. 5a, while in Fig. 5b the normalization is to the fourth family scenario. The cut on the BDT output is chosen to have similar levels of background as the cut-based analysis. Given the better discriminating power

Table 5: Numbers of events observed in 36 pb^{-1} of data, with the signal and background predictions after $H \rightarrow W^+W^-$ selections in both cut-based and multivariate approaches. Only statistical uncertainties from the simulations are included.

m_H (GeV/c^2)	data	SM $H \rightarrow W^+W^-$	SM with 4th gen. $H \rightarrow W^+W^-$	all bkg.	$qq \rightarrow W^+W^-$	$gg \rightarrow W^+W^-$	all non-W^+W^-
cut-based approach							
130	1	0.30 ± 0.01	1.73 ± 0.04	1.67 ± 0.10	1.12 ± 0.01	0.10 ± 0.01	0.45 ± 0.10
160	0	1.23 ± 0.02	10.35 ± 0.16	0.91 ± 0.05	0.63 ± 0.01	0.07 ± 0.01	0.21 ± 0.05
200	0	0.47 ± 0.01	3.94 ± 0.07	1.47 ± 0.09	1.13 ± 0.01	0.12 ± 0.01	0.23 ± 0.09
210	0	0.34 ± 0.01	2.81 ± 0.07	1.49 ± 0.05	1.09 ± 0.01	0.10 ± 0.01	0.30 ± 0.05
400	0	0.19 ± 0.01	0.84 ± 0.01	1.06 ± 0.03	0.79 ± 0.01	0.04 ± 0.01	0.23 ± 0.03
multivariate approach							
130	1	0.34 ± 0.01	1.98 ± 0.04	1.32 ± 0.18	0.75 ± 0.01	0.04 ± 0.00	0.53 ± 0.18
160	0	1.47 ± 0.02	12.31 ± 0.17	0.92 ± 0.10	0.63 ± 0.01	0.06 ± 0.00	0.22 ± 0.10
200	0	0.57 ± 0.01	4.76 ± 0.07	1.47 ± 0.07	1.07 ± 0.01	0.13 ± 0.00	0.27 ± 0.07
210	0	0.42 ± 0.01	3.47 ± 0.07	1.44 ± 0.07	1.03 ± 0.01	0.12 ± 0.00	0.29 ± 0.07
400	0	0.20 ± 0.01	0.90 ± 0.01	1.09 ± 0.07	0.75 ± 0.01	0.04 ± 0.00	0.30 ± 0.07



(a)



(b)

Figure 5: BDT outputs for Higgs boson signal and for backgrounds, for (a) $m_H = 160$ GeV/c^2 and (b) $m_H = 200$ GeV/c^2. The Higgs boson event yield is normalized (a) to the SM expectation, and (b) to the fourth family scenario. The area marked as W^+W^- corresponds to the nonresonant contribution.

of the BDT analysis, the corresponding signal yields for each Higgs boson mass are about 15% higher than those obtained using the cut-based selection. The numbers of events observed in 36 pb^{-1} of data and the signal and background predictions are compared in Table 5.

5.2 Background estimation

The nonresonant W^+W^- contribution in the $H \rightarrow W^+W^-$ signal region is estimated from data using the dilepton mass distribution. For a given Higgs boson mass, the region with a small contribution from Higgs boson decays is selected and simulation is used to extrapolate this background into the signal region. For low Higgs boson mass values ($m_H < 200$ GeV/c^2) events with $m_{\ell\ell} > 100$ GeV/c^2 are used, while for $m_H > 200$ GeV/c^2 events with $m_{\ell\ell} < 100$ GeV/c^2 are used. The statistical uncertainty on the estimate of the nonresonant W^+W^- background with the current data sample is approximately 50%.

The non-W^+W^- backgrounds are estimated in the same way as in the W^+W^- production cross section measurement described in Section 3.2. The $W+$jets, QCD and Drell–Yan $Z/\gamma^* \rightarrow \ell^+\ell^-$ backgrounds are estimated using data. For each studied Higgs mass region, the W^+W^- background estimated in the complementary mass region is then extrapolated into the studied region, taking into account the effects of the selection criteria, as determined from simulation.

In addition, for the present measurement other Higgs boson production mechanisms are considered as backgrounds: a Higgs boson in the final state accompanied by a W or Z boson or by a pair of top quarks, and the vector boson fusion process. These processes are heavily suppressed by the jet and additional lepton veto requirements, and the corresponding yield amounts to 1–2% of the gluon fusion process.

5.3 Systematic uncertainties

Systematic uncertainties related to acceptance and efficiencies for $H \rightarrow W^+W^-$ are estimated in a similar way as described in Section 3.3.

Simulated events are used to predict the $H \rightarrow W^+W^-$ signal efficiency, and $Z \rightarrow \ell^+\ell^-$ events are used to study the data-to-simulation efficiency scale factors of the lepton selection and jet veto requirement. Due to details in the implementation of the POWHEG calculation [45], the resulting Higgs boson p_T spectrum is harder than the most precise spectrum calculated [46] to NNLO with resummation to next-to-next-leading-log (NNLL) order. Therefore, the Higgs boson p_T distribution is reweighted in POWHEG to match the NNLO+NNLL prediction. The signal efficiency, estimated after this reweighting, is 14% larger than that from uncorrected POWHEG calculations, and it is independent of the Higgs boson mass.

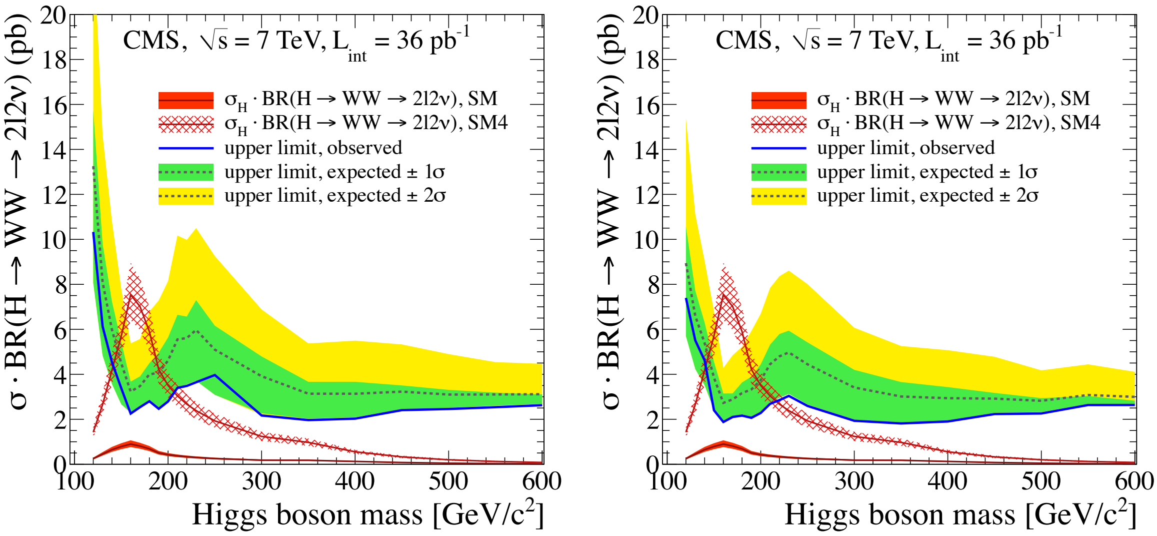
The overall uncertainty on the $H \rightarrow W^+W^-$ signal yield is estimated to be of about 14%, where the uncertainty on the jet veto efficiency and the luminosity determination are the main contributions. The uncertainties on the background estimations in the $H \rightarrow W^+W^-$ signal regions are about 40%, dominated by statistical uncertainties in the data control regions.

5.4 Results

Upper limits are derived on the product of the gluon fusion Higgs boson production cross section by the $H \rightarrow W^+W^-$ branching fraction, $\sigma_H \cdot \mathrm{BR}(H \rightarrow W^+W^- \rightarrow 2\ell 2\nu)$. Two different statistical methods are used, both using the same likelihood function from the expected number of observed events modeled as a Poisson random variable whose mean value is the sum of the contributions from signal and background processes. The first method is based on Bayesian inference [47], while the second method, known as CL_s, is based on the hybrid Frequentist-Bayesian approach [48]. Both methods account for systematic uncertainties. Although not identical, the upper limits obtained from both methods are very similar. Results are reported in the following using only the Bayesian approach, with a flat signal *prior*.

The 95% observed and mean expected C.L. upper limits on $\sigma_H \cdot \mathrm{BR}(H \rightarrow W^+W^- \rightarrow 2\ell 2\nu)$ are given in Table 6 for several masses, and shown in Fig. 6 for Higgs boson masses in the range 120-600 GeV/c^2. Results are reported for both the cut-based and the BDT event selections, along with the expected cross sections for the SM case and for the fourth-fermion family case. The bands represent the 1σ and 2σ probability intervals around the expected limit. The *a posteriori* probability intervals on the cross section are constrained by the *a priori* minimal assumption that the signal and background cross sections are positive definite. The expected background yield is small, hence the 1σ range of expected outcomes includes pseudo-experiments with zero observed events. The lower edge of the 1σ band therefore corresponds already to the most stringent limit on the signal cross section, and fluctuations below that value are not possible.

The $\sigma_H \cdot \mathrm{BR}(H \to W^+W^- \to 2\ell 2\nu)$ upper limits are about three times larger than the SM expectation for $m_H = 160$ GeV/c^2. When compared with recent theoretical calculations performed in the context of a SM extension by a sequential fourth family of fermions with very high masses [8, 49], the results of BDT analyses exclude at 95% C.L. a Higgs boson with mass in the range from 144 to 207 GeV/c^2. Similar results are achieved using the cut-based approach. The drop in the expected cross section upper limit in the Higgs boson mass region between 200 and 250 GeV/c^2 is due to the lower signal efficiency while the background expectation remains at similar levels.



(a) (b)

Figure 6: 95% mean expected and observed C.L. upper limits on the cross section $\sigma_H \cdot \mathrm{BR}(H \to W^+W^- \to 2\ell 2\nu)$ for masses in the range 120-600 GeV/c^2 using (a) cut-based and (b) multivariate BDT event selections. Results are obtained using a Bayesian approach. The expected cross sections for the SM and for the SM with a fourth-fermion family cases (SM4) are also presented. The dash line indicates the mean of the expected results.

Table 6: 95% observed and mean expected C.L. upper limits on the cross section $\sigma_H \cdot \mathrm{BR}(H \to W^+W^- \to 2\ell 2\nu)$ for four Higgs masses. The results of the cut-based and the multivariate-based event selections are obtained using a Bayesian approach. The expected production cross sections for a SM Higgs boson [50] and for the scenario with an additional fourth family of fermions are also included.

m_H (GeV/c^2)	$\sigma \cdot BR$ SM (pb)	$\sigma \cdot BR$ 4th gen. (pb)	lim. obs. cut-based (pb)	lim. exp. cut-based (pb)	lim. obs. BDT-based (pb)	lim. exp. BDT-based (pb)
130	0.45	2.66	6.30	8.07	5.66	6.57
160	0.90	7.54	2.29	3.22	1.93	2.72
200	0.42	3.50	2.80	4.59	2.32	3.72
210	0.37	3.04	3.41	5.53	2.76	4.43
400	0.13	0.55	2.08	3.12	1.94	2.93

6 Summary

This paper reports the first measurement of the W^+W^- cross section and a search for the Higgs boson decaying to W^+W^- in pp collisions at $\sqrt{s} = 7$ TeV, in a data sample corresponding to an integrated luminosity of 36 pb^{-1}. Thirteen W^+W^- candidate events, where both W bosons decay leptonically, have been observed in the signal region, with an estimated background contribution of 3.29 ± 0.45 (stat) ± 1.09 (syst). The W^+W^- cross section has been measured to be 41.1 ± 15.3 (stat) ± 5.8 (syst) ± 4.5 (lumi) pb, consistent with the SM prediction.

The W^+W^- events have been used to measure the $WW\gamma$ and WWZ triple gauge couplings. The results, which are in agreement with the SM predictions, are consistent with the precise measurements made at LEP and comparable in sensitivity with the current Tevatron results.

Limits on the Higgs boson production cross section have been derived. No excess above the SM expectations was found. In the presence of a sequential fourth family of fermions with very high masses, a Higgs boson with standard model couplings and a mass between 144 and 207 GeV/c^2 has been excluded at 95% confidence level.

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29: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
30: Also at University of Athens, Athens, Greece
31: Also at The University of Kansas, Lawrence, USA
32: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
33: Also at Paul Scherrer Institut, Villigen, Switzerland
34: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
35: Also at Gaziosmanpasa University, Tokat, Turkey
36: Also at Adiyaman University, Adiyaman, Turkey
37: Also at Mersin University, Mersin, Turkey
38: Also at Izmir Institute of Technology, Izmir, Turkey
39: Also at Kafkas University, Kars, Turkey
40: Also at Suleyman Demirel University, Isparta, Turkey
41: Also at Ege University, Izmir, Turkey
42: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
43: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
44: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
45: Also at Institute for Nuclear Research, Moscow, Russia
46: Also at Los Alamos National Laboratory, Los Alamos, USA